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# Latest Developments in Nuclear Emulsion Technology

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**Abstract**

Nuclear emulsion is high sensitive photographic film used for detection of three-dimensional trajectory of charged particles. These trajectories are recorded as tracks consist of a lot of silver grains. The size of silver grain is about 1 μm, so that nuclear emulsion has submicron three-dimensional spatial resolution, which gives us a few mrad three-dimensional angular resolution. The important technical progress was speed-up of the read-out technique of nuclear emulsions built with optical microscope system. We succeeded in developing a high-speed three-dimensional read-out system named Super Ultra Track Selector (S-UTS) with the operating read-out speed of approximately 50 $cm^2$/h. Nowadays we are developing the nuclear emulsion gel independently in Nagoya University by introducing emulsion gel production machine. Moreover, we are developing nuclear emulsion production technologies (gel production, poring and mass production). In this paper, development of nuclear emulsion technologies for the OPERA experiment, applications by the technologies and current development are described.

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*Keywords:* nuclear emulsion, muon radiography, neutron, proton, fast ion, scanning system ;

## 1. Nuclear Emulsion

Nuclear emulsion is one of photographic films, which is able to detect three-dimensional tracks of charged particles with submicron spatial resolution (Fig. 1 (a)). The structure of nuclear emulsion is shown in Fig. 1 (b). Emulsion gel is poured on the supporting base material (Fig. 1 (d)). A lot of silver bromide (AgBr) crystals, which diameter is a few hundred nm, are dispersed in gelatin layer (Fig. 1 (e)). Fig. 1 (c) is electron microscope picture of AgBr crystals. A charged particle passes through emulsion layer, as a result, some crystals in the line of trajectory have latent image. After chemical development of nuclear emulsion, these latent images change to submicron silver particles (grains) (Fig. 1 (f)). From this principle, we can detect three-dimensional trajectory of charged particle

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(track). The optical microscope image of track is presented in Fig. 1 (g). Due to the excellent performance as a detector with submicron position accuracy in 4π solid angle, nuclear emulsion allowed to observe π and μ decays (Powell, Fowler and Perkinset (1959)), charmed particle (Niu et al. (1971)), tau neutrino (Kodama et al. (2002)), double hypernucleus (Takahashi et al. (2001)) and so on.

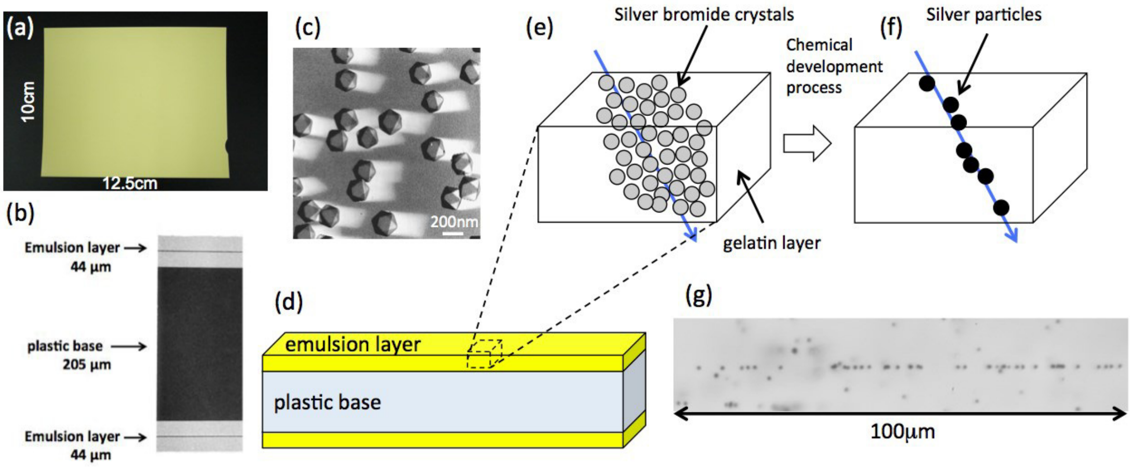


Fig. 1. (a) A picture of OPERA film; (b) An electro microscope image of cross section of OPERA film; (c) An electron microscope image of silver bromide crystals of OPERA film. The diameter of crystals is about 200 nm; (d) An Illustration of the structure of OPERA film; (e) and (f) The principle of detection of charged particle; (g) A microscope image of track of minimum ionizing particle in OPERA film.

## 2. Technical development for the OPERA experiment

The aim of the OPERA experiment is direct observation of tau neutrino appearance in a pure muon neutrino beam (Acquafredda et al. (2009)). The principle of the OPERA detector operation is the following. Neutrino has very small cross-section. In order to detect enough neutrino interactions for analysis and to realize this experiment, 1000 tons of target materials are needed. On the other hand, in order to identify tau neutrino, we need to observe tau decay. Tau decay scale is about 1mm, and decay kink angle is several 10 mrad. Thus, a detector with micron spatial resolution is needed. The only detector satisfying both requirements is Emulsion Cloud Chamber (ECC), which is stacking structure of nuclear emulsion and target material plates. OPERA ECC consists of 57 emulsion films interleaved with 1mm thick lead plates and the size of both plates is 10 cm × 12.5 cm. In order to realize this experiment, 8 million nuclear emulsion plates were necessary.

### *2.1. OPERA film*

8 million plates were produced by Fuji Photo Film Co., Ltd and were named OPERA film. OPERA film is first case of industrial machine production (Nakamura et al. (2006)). Fig. 1 (b) shows the nuclear emulsion cross section under the electron microscope. Emulsion layers, which are able to record trajectory of charged particle, are very uniformly poured on both sides of plastic supporting base and uniformity of thickness is less than 1 μm. The density of Ag grains per 100 μm of minimum ionization particle (MIP) track is 36. This value is the unit of sensitivity of nuclear emulsion called Grain Density (GD).

### *2.2. Automated scanning system "S-UTS"*

The OPERA experiment requires not only industrial production of nuclear emulsion but also a high-speed data analysis as well. The required speed is about 1000 $cm^2$/day. We have developed high-speed emulsion read-out system named Super Ultra Track Selector (S-UTS) in order to fulfill the requirement (Morishima and Nakano (2010); Hamada et al. (2012); Morishima et al. (2013)) (Fig. 2 (a)). The system takes tomographic images divided into sixteen layers with changing the focal plane in the emulsion layer by moving the objective lens as shown in Fig. 2 (b). By using these tomographic images, straight chain of grains is distinguished as tracks. After track recognition, track data (position, angle, pulse height) is saved into the database. After taking data, we perform the three-dimensional track reconstruction in the emulsion detector volume as shown in Fig. 2 (c). By using the track data, we perform the selection of tracks from high-energy particles by using momentum calculated by measuring angle of multiple coulomb scattering and connect tracks reconstructed on each nuclear emulsion. And then, we perform the search of interaction point (vertex) with high-energy tracks in the scanned volume. Finally, by using vertex data, we perform search and reconstruction of tau neutrino interactions (Agafonova et al. (2009, 2010)).

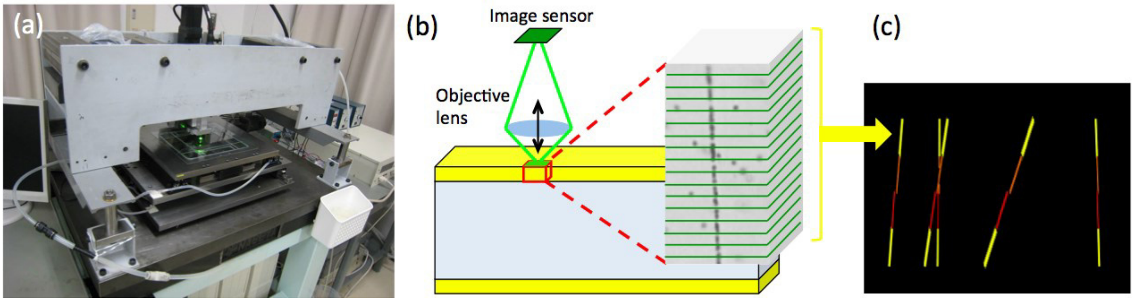


Fig. 2. (a) A picture of S-UTS; (b) The conceptual diagram of taking tomographic images in emulsion layer; (c) Reconstructed track displayed in 3D viewer. Yellow lines show recognized tracks in emulsion layer and red lines show virtual connection line in base between two tracks.

### 2.3. Applications

Nuclear emulsion technologies developed for the OPERA experiment enable us to apply nuclear emulsions to various fields. This section is devoted to the applications for cosmic-ray muon radiography and fast ion detector.

#### 2.3.1. Cosmic-ray muon radiography

Cosmic-ray muon radiography is a non-destructive inspection technique similar to x-ray imaging for large-scale objects. A muon is one of the fundamental particles and has high penetration power. For example, muon with an energy of 1 TeV is able to pass through 1km of rocks. Muons are produced in the interaction of primary cosmic rays and atoms of the atmosphere. Cosmic-ray muons produced by this mechanism come to the ground level from all sky direction. Incoming muon flux and angular distribution are already well known. By measuring the direction and the number of detected muons at the observation point, the absorption rate can be estimated (Fig. 3 (a)). From this absorption rate, the density length ($g/cm^2$) can be calculated in each direction. First observation of muon radiography with nuclear emulsion was conducted to Mt. Asama in Japan and inner density image of mountain was successfully taken (Tanaka et al. (2007)).

We proposed to use the muon radiography method for nuclear reactor observation at Fukushima Daiichi Nuclear Power Plant. The object of study is the imaging of the inside of the nuclear reactor. The situation inside the reactors is not understood exactly. However, it is impossible to observe directly inside the reactor, due to high radioactivity. Thus, muon radiography is the only indirect measurement method. The problems to be solved are the shielding from high radioactivity, power supply and lack of space. These problems can be solved with a help of nuclear emulsion due to its three advantages: thin detector with high angular resolution, light weight, and no need of power supply. Thus, these properties make nuclear emulsion ideal for use at a place like Fukushima Daiichi Nuclear Power Plant. We have conducted a test observation in order to validate the muon radiography method with OPERA film at the experimental fast reactor Joyo, which belongs to Japan Atomic Energy Agency, in Japan (Morishima et al. (2012)). On base of the experimental result, we started to apply cosmic-ray muon radiography with new nuclear emulsion, which has high sensitivity to MIP and is described in the next section, to Fukushima Daiichi Nuclear Power Plant with Toshiba Co., Ltd.

*2.3.2. Fast neutron, proton and heavy ion detector*

Nuclear emulsions can be applied to the measurement of ions that are proton and heavy ions. And also fast neutron can be measured by detection of proton recoiled by fast neutron. Measurement of protons was applied to linear energy transfer (LET) measurement by using radiotherapy accelerator (Shin et al. (2015)) (Fig. 3 (b)). Measurement of fast neutron was applied to nuclear fusion plasma diagnostics (Morishima et al. (2013); Isobe et al. (2013); Tomita et al, (2013)) (Fig. 3 (c)). Measurement of heavy ions was applied to the basic study of heavy particle radiotherapy (Toshito et al. (2006)).

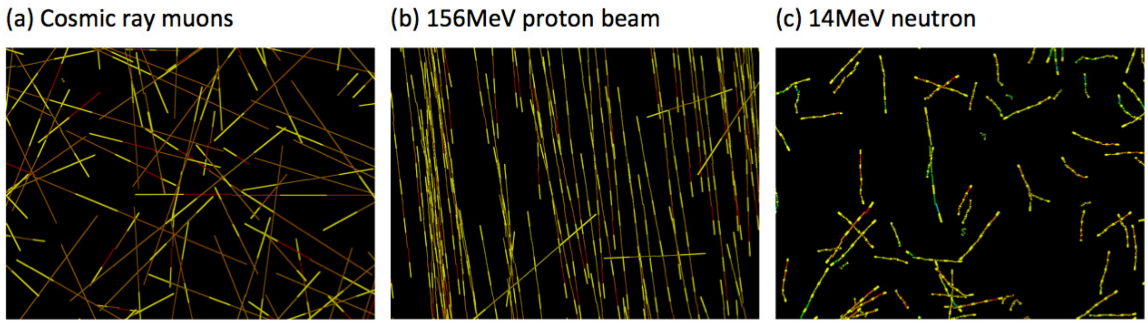


Fig. 3. Reconstructed tracks displayed in 3D viewer. (a) Cosmic ray muons measured on the ground. These tracks are seen in various angles; (b) 156 MeV proton beam by accelerator. These tracks are seen in parallel; (c) 14 MeV D-T neutrons by nuclear fusion reaction. Neutrons were irradiated to the nuclear emulsion almost in parallel and recoiled proton tracks are seen in various angles.

## 3. Current development

This section is devoted to the on-going development of nuclear emulsion technologies in Nagoya University. Because OPERA film is not manufactured now, we started the development of fully self-made emulsion technologies. Fig. 4 (a) shows the cross section of our new nuclear emulsion. 170 μm thick polystyrene (PS) plastic base is used. This structure is almost identical to the OPERA film. We are developing high sensitive nuclear emulsion gel for detection of MIP, pouring technique and mass production method.

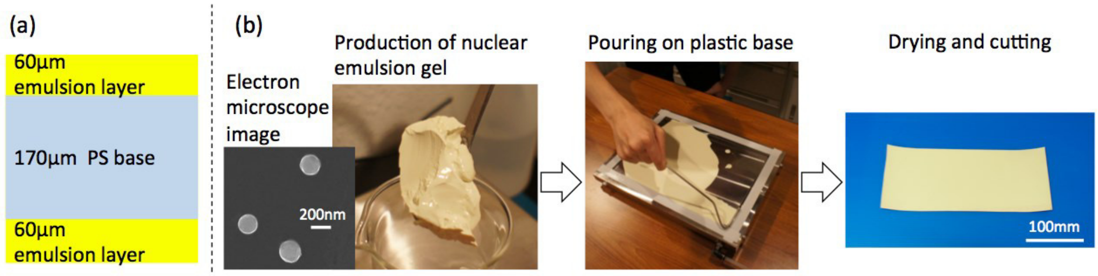


Fig. 4. An overview of new self-made nuclear emulsion. (a) A cross section of nuclear emulsion; (b) A production process of nuclear emulsion.

### 3.1. High sensitive emulsion gel

We have put emulsion gel production machine into operation in our laboratory at 2010 and nowadays are able to produce emulsion gel independently. By using the machine, we are studying improvement of performances (sensitivity, background noise and long-term stability) for purposes. The picture of Fig. 4 (b) shows produced emulsion gel and an electron microscope image of silver bromide crystals. For detection of MIP, crystals of about 200 nm in diameter are produced and are sensitized. The track recognition efficiency of scanning system can be improved by increasing GD. In order to increase GD, the volume occupancy of AgBr crystals in nuclear emulsion layer was increased from 30% in case of OPERA film to 55 %. In addition, additive amount of chemicals such as surfactant and plasticizer was tuned to prevent emulsion layer from cracking. Fig. 5 shows the microscope image of MIP track in new emulsion. The GD is $51 \pm 2$ and higher than that of OPERA film.

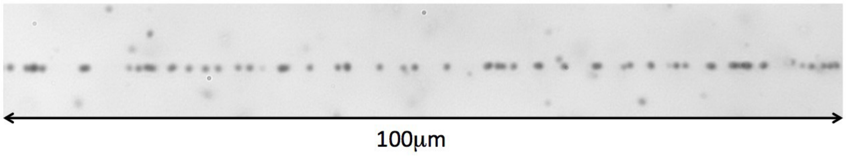


Fig. 5. A microscope image of track of minimum ionizing particle in high sensitive nuclear emulsion

### 3.2. Pouring technique

We developed pouring techniques in two ways. The first way is traditional one. The procedure is shown in Fig. 6 (a). We pour emulsion gel inside frame made of vinyl tape and spread by using the tool. After that, we perform drying process. The second way is the new method. We developed new coating tool in order to spread emulsion gel with keeping the uniformity of the emulsion layer thickness. The procedure is shown in Fig. 6 (b). As seen in the figure, the process is very easy and includes just pouring gel into the box and moving the tool with keeping constant speed. After that, we perform drying process. Each achieved uniformity of the thickness is about 10 μm by traditional method and about 2 μm by new method in the area of 10 cm × 10 cm. Uniformity of thickness of new method is better than traditional method and is almost same as OPERA film. In order to improve the production speed and reduce dependence on individual differences of skills, mechanical pouring technologies based on the new method with combination of air-conditioning control system are under development.

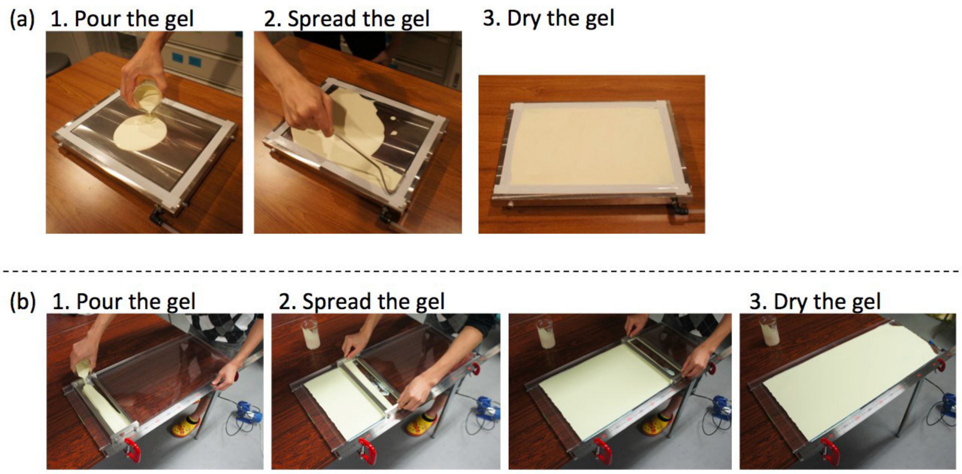


Fig. 6. Pouring techniques. (a) Traditional method; (b) New method.

### 3.3. Mass production

We performed mass production of nuclear emulsion in Nagoya University in the period from January to December in 2014 for cosmic-ray muon radiography and gamma ray telescope experiment with nuclear emulsion (Aoki et al. (2008)). In this period, we have produced emulsion gel of about 200 kg and made nuclear emulsions by traditional pouring method through a trial and error. The production volume is corresponding to about 150 $m^2$ of nuclear emulsions with the thickness of 50 μm. Mass production speed was about $4m^2$/week. In the cosmic-ray muon radiography experiment, 12.5 cm × 30 cm size nuclear emulsions, which is shown in Fig. 4 (b), are produced and about 15 $m^2$ are already used.

## 4. Conclusions

Through development of nuclear emulsion technologies for the OPERA experiment, a huge amount of nuclear emulsions named OPERA film was produced and a high-speed scanning system named S-UTS was developed. Thanks to these technologies, application of nuclear emulsion was expanded to various fields such as cosmic-ray muon radiography, fusion plasma diagnostics and so on. Nowadays, we introduced nuclear emulsion gel production machine in Nagoya University and are developing high performance nuclear emulsion gel, pouring technologies and mass production method. And also we developed high sensitive nuclear emulsion (GD is $51\pm2$) to MIP. The new high sensitive nuclear emulsions are produced and are already used to the cosmic-ray muon radiography.

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